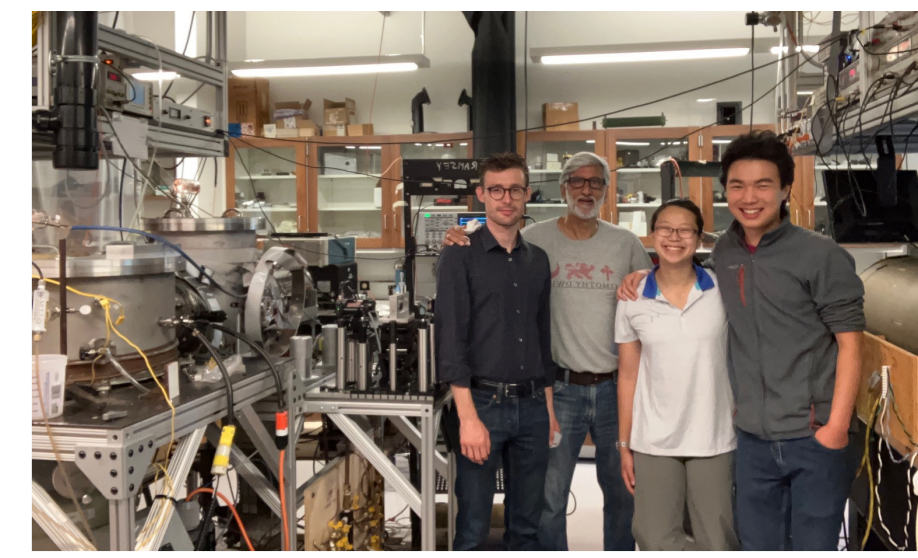




Precise atomic structure measurements in Pb using vapor-cell and atomic-beam spectroscopy



John H. Lacy, Abby Kinney* '24, Robin Wang† '24, Charles Yang# '24, and P. K. Majumder

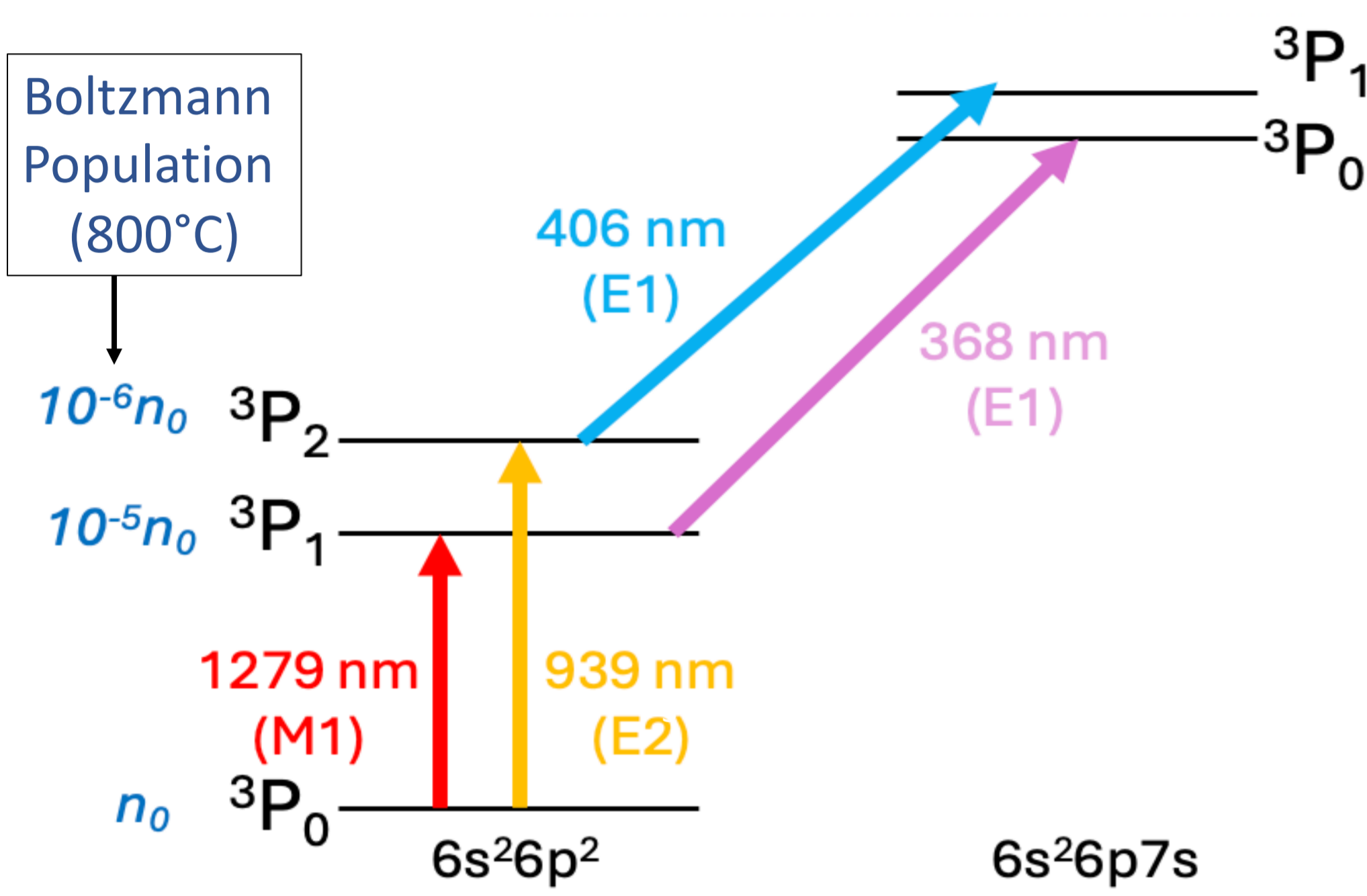
Department of Physics, Williams College, Williamstown, MA 01267 USA

* → Physics Dept., U. Chicago; † → QSE program, Harvard Univ.; # → Physics Dept., Rice Univ.

Background

- Heavy, multivalence elements are good testbeds for testing fundamental particle physics interactions → effects scale as $\sim Z^3$. → Atomic theory is challenging!
- Previous work with Group IIIA In and Tl tested *ab initio* multi-valence wavefunction models (Majumder + Safronova group collaborations).
- New focus is on Group IV Pb (two existing precise PNC experimental results). Improved atomic theory, but requires new, accurate experimental benchmarks...

Pb energy levels (group IV)



- ❖ $M1$ amplitude precisely calculable: $1.293(1)$ a.u.
- ❖ $E2/M1$ measured by us using Faraday Rotation in 2019
 - $\langle E2 \rangle_{exp} = 8.91(9)$ a.u.
 - $\langle E2 \rangle_{th} = 8.88(5)$ a.u. (Safronova group)
- ❖ Note: $E1$ transition amplitude measurements require accurate determination of thermal population

E1 transition amplitudes of (thermally) excited states using Faraday rotation spectroscopy

Experimental setup

1f signal $\propto I(\nu)\Phi_F(\nu)\Phi_m$
2f signal $\propto I(\nu)\Phi_m^2$
→ [1f/2f] $\propto \Phi_F(\nu)/\Phi_m$

Faraday line shape Modulation amplitude

Results

Extracting the matrix element

$$\frac{\Phi_0^{E1}}{\Phi_0^{M1}} = \frac{C_{E1}^0(\Gamma, \sigma_D, B, T)}{C_{M1}^0(\Gamma, \sigma_D, B, T)} \frac{n_0 e^{-\frac{0.970 \text{ eV}}{kT}}}{n_0} \frac{\omega_{E1}}{\omega_{M1}} \left(\frac{ea_0}{\mu_B/c}\right)^2 \frac{\langle E1 \rangle^2}{\langle M1 \rangle^2}$$

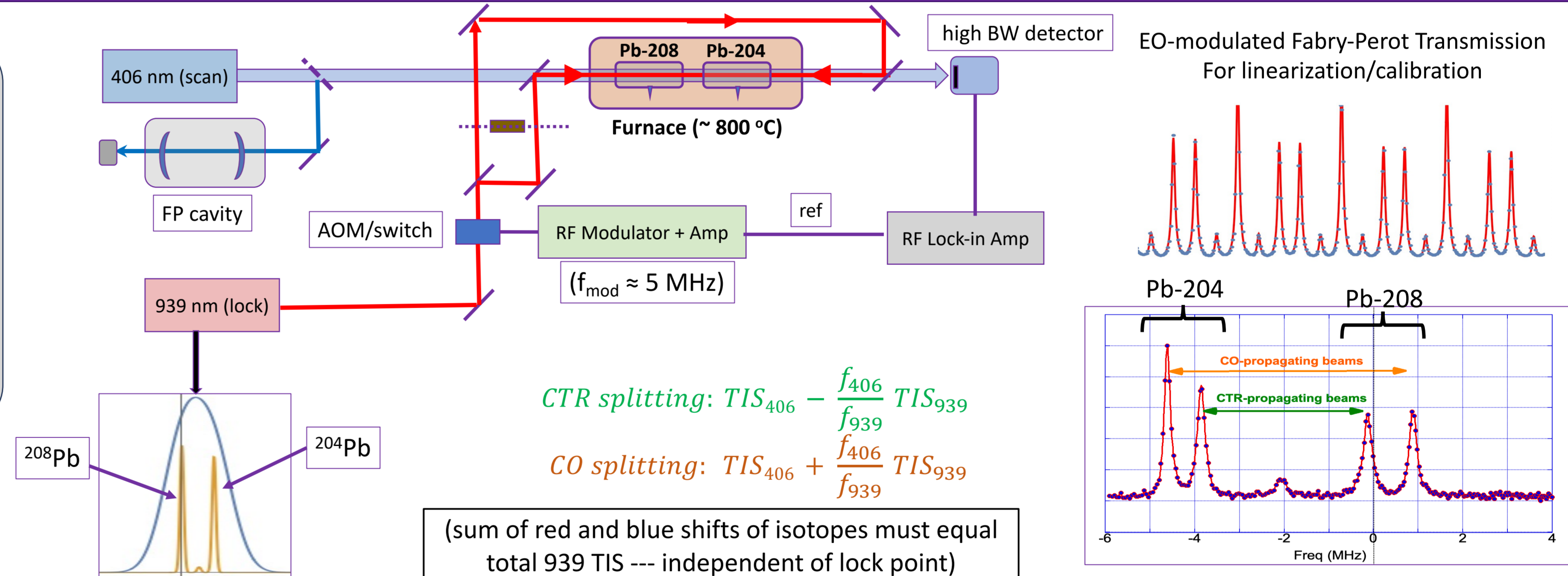
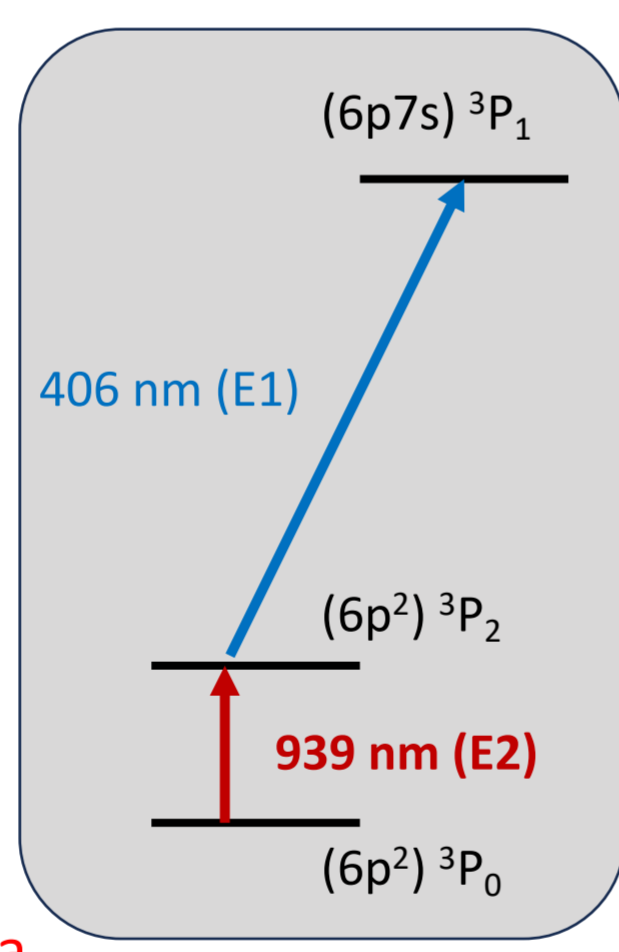
Peak optical rotation (from line shape fit) Line shape factors (from line shape fit) Boltzmann factor (fixed)** Transition frequencies (known) atomic units $\langle M1 \rangle$ precisely calculable

****Temp. (and Boltzmann factor) well controlled**

- 3-zone heating elements for 'uniformity'
- → overall Temp variance/accuracy: $\sim \pm 1$ °K
- → $\sim 0.5\%$ contribution to $\langle E1 \rangle$ uncertainty

Isotope shift measurements in heated Pb vapor cells using Doppler-free, two-step spectroscopy

- Thermal population for 3P_2 state is $\sim 10^{-6}$.
- Pumping E2 transition with 939 diode laser increases this to $\sim 10^{-4}$.
- 'Chop' 939 (locked) laser → lock-in detection of 406 transmission signal
- Pb-Pb mean collision time ~ 5 μ sec for vapor cell @ 850 °C

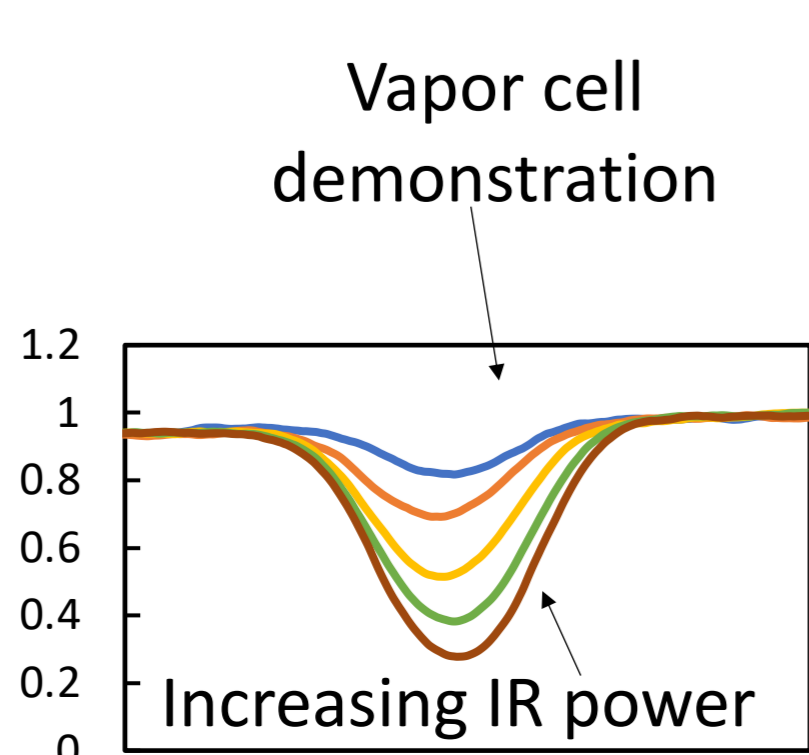
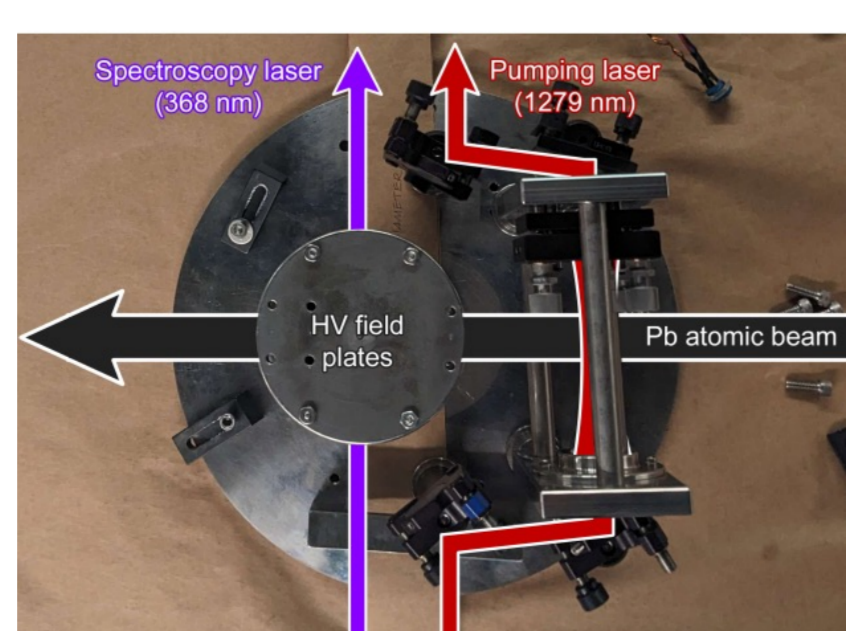


15 mins of preliminary data: $TIS_{406} = 4589(2)$ MHz;
 $TIS_{939} = 379.5(5)$ MHz – first ever direct measurement

Ongoing atomic beam work in Pb

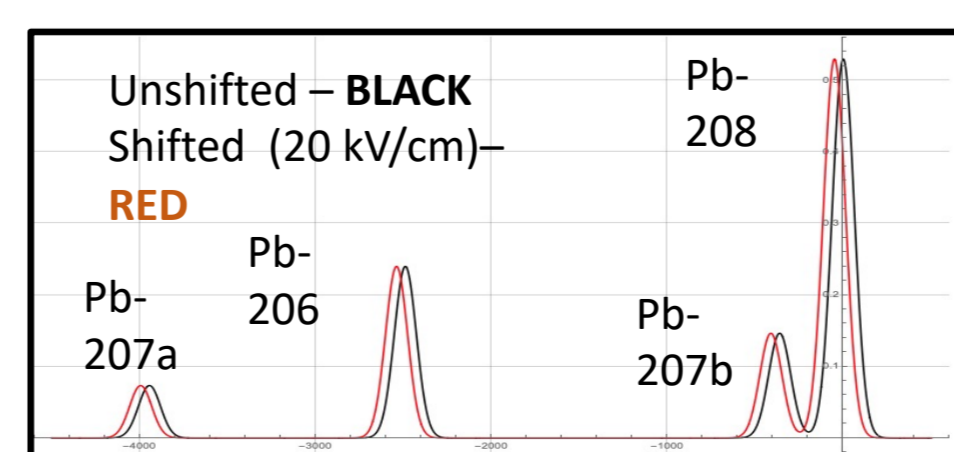
Polarizability measurements in atomic beam unit

- Quadratic Stark shift measurements: $\Delta E = -\frac{1}{2}\alpha_0 \mathcal{E}^2$ - excellent benchmark test of theory.
- Expected shift of ~ 50 MHz for $^3P_1 \rightarrow (6p^7s)^3P_0$ E1 transition with $\mathcal{E} \approx 20$ kV/cm - easily resolvable
- Enhance UV signal by pumping the $(6p^2)^3P_0 \rightarrow ^3P_1$ transition

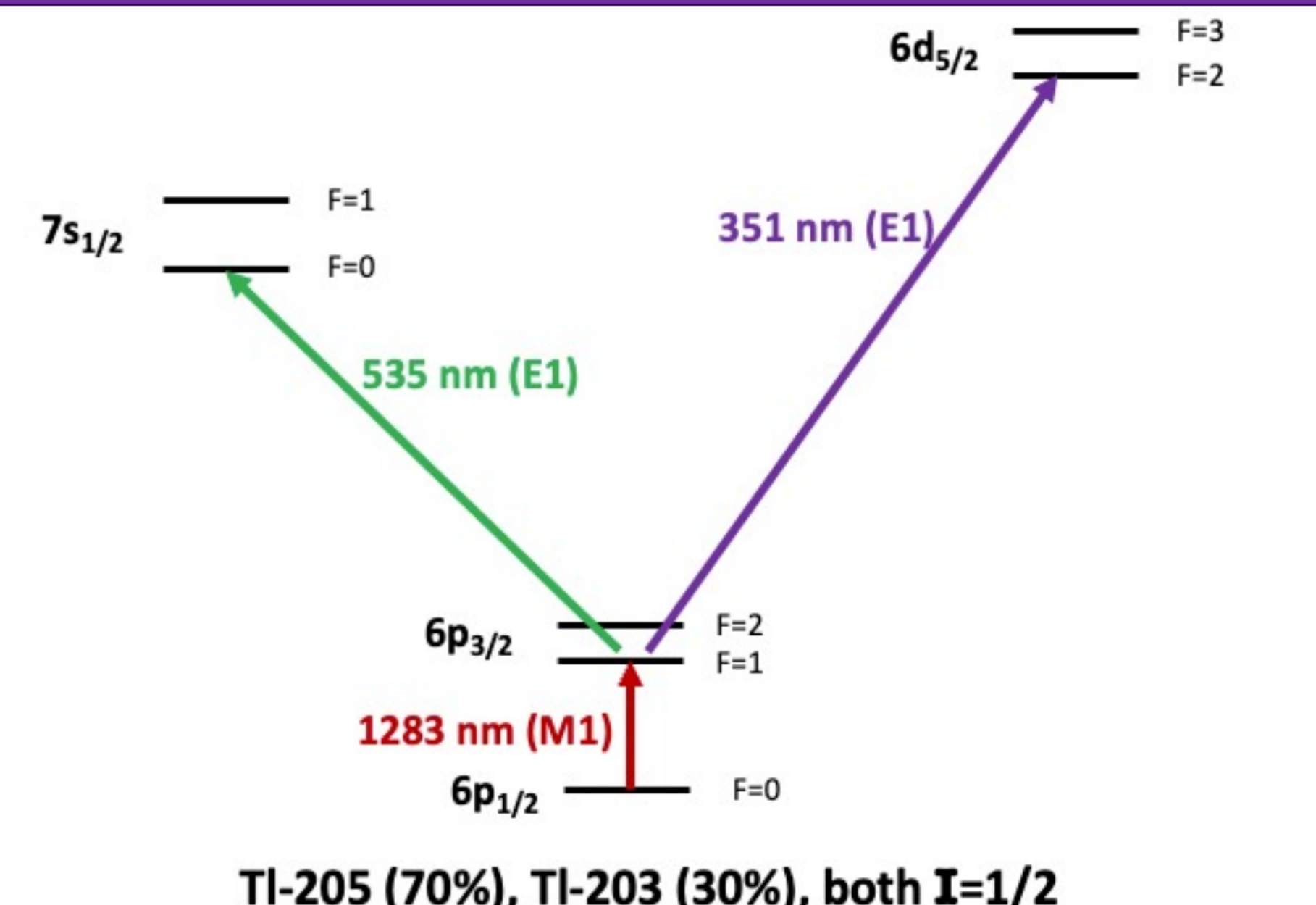


Quantity (rel. to vapor cell @ 800 °C)	Vapor cell in furnace	Atomic beam (@ 1050 °C)
Peak absorption cross section	σ_0	$\sigma_0 \times 10$ (Doppler narrowing)
3P_1 number density	n_0	$n_0 \times 50$ (M1 pre-pumping) $\times 10$ (thermal/Boltzmann) $\times 10^{-4}$ (Geometrical loss)
Interaction length	ℓ	$\ell \times 0.2$ (atomic beam width)
Optical depth	1	0.01 - 0.1

Indium ABU / polarizability results: 2013, 2016, 2018



Future work in Tl



- $E1/M1$ transition amplitude ratios
- 205/203 transition isotope shifts using Doppler free two-step spectroscopy (as above)